WinCD:

COMPLEX DEMODULATION TIME-SERIES ANALYSIS FOR WINDOWS™

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Complex Demodulation Time-Series Analysis for Windows™

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ABSTRACT

This document describes WinCD, a program for extracting quantitative information about periodicity in time-series data using the method of Complex Demodulation (CD). The method is particularly well-suited for the analysis of variables that may produce changes in biological rhythms, such as sleep deprivation, adaptation to changes in work schedules, time-zone displacements, and various sorts of pathology (e.g., sleep disorders). WinCD enables exploratory analysis of time-series data by providing graphical displays of raw and processed time series, as well as numerous options for viewing and saving quantitative data. This document presents detailed descriptions of WinCD operations, examples of the use of the program, a discussion of CD theory and background, and a glossary of CD terms. The program and documentation are available for free distribution to interested parties.

INTRODUCTION

This manual describes **WinCD**, Version 1.0, a Microsoft® Windows™-based computer program for analysis of time-series data on IBM™-compatible microcomputers using complex demodulation (CD). CD is a method of analyzing time-series data that extracts information about temporal regularities in the data. In this regard it is similar to other methods for time-series analysis such as autocorrelation, Fourier analysis, or Cosinor analysis. These methods are frequency-domain analyses that yield information about the presence and magnitude of periodic influences in the data but sacrifice information regarding the temporal dynamics of the time series. In contrast, CD is an approach to time series analysis that is explicitly designed for analysis of non-stationary time series, and is the digital equivalent of a band-pass filter in electronics. Thus, when a time series is subjected to CD at a given frequency, frequencies other than the chosen one are eliminated from the time series (or greatly attenuated), leaving only the chosen frequency. Appendix 1 provides a more detailed description of the CD process. CD is able to capture the rhythmic aspects of dynamically changing time series that are observed when fundamental variables controlling rhythmic processes are manipulated. CD analysis is especially well suited to studies of sleep deprivation, work schedule changes (e.g. switching from a day shift to a night shift), and time-zone displacements.

Origins of WinCD

In the 1980s, Helen Sing of the Walter Reed Army Institute of Research wrote a FORTRAN program, **DEMODGEN**, to do complex demodulation. This program has been used extensively on both main-frame and personal computers for doing CD analyses. The purpose of this manual is to describe a new CD program, **WinCD**, written in Visual BASIC™ for Windows, by Tim Elsmore in consultation with Paul Naitoh of the Naval Health Research Center, and Fred Hegge, Helen Sing, and David Thorne at the Walter Reed Army Institute of Research. WinCD is based on the computational algorithms of **DEMODGEN**, and takes advantage of the greatly improved user interface made possible by the Windows computing environment. Some familiarity with Microsoft Windows is desirable for the use of WinCD.

Limitations of WinCD

WinCD can be used for analysis of *any* time series as long as it has an adequate number of data points and they were sampled at *equal* time intervals. WinCD cannot *accurately* process irregularly sampled time series although it will produce results with such data. As with other forms of time-series analysis, the sampling rate determines the fastest frequency that can be analyzed. The low-frequency limitation for WinCD is determined by the reciprocal of the total number of observations in the time series and the interval between observations (the epoch). For example, if one observation is made every hour for one day, there will be 24 data points, and the lowest frequency that can be processed by WinCD will be one cycle per day. In most cases observations will be made over multiple days to observe dynamic changes in the frequency of interest as a result of some manipulation.

System Requirements and Installation

WinCD requires an IBM-Compatible PC and Windows 3.1 or better. The software is distributed on a single 3.5 inch floppy disk. Insert the disk in the appropriate drive, and from within Windows execute the program "SETUP.EXE" on the floppy disk using either the "Run" command (**File: Run**) or the Windows File Manager. This will create a directory on your hard disk (C:\CD) and copy files from the floppy to the new directory. In addition to the "CD.EXE" file, the installation routine will also put some sample data files in this directory. It will also place two files, "VBRUN300.DLL" and "THREED.VBX," in your "C:\windows\system" directory. The installation procedure creates a CD Program Group in the Windows Program Manager, and places the WinCD icon in

this program group. WinCD is started by double-clicking on this icon. If desired, you may drag the WinCD icon to a different program group (e.g., "Applications") and delete the WinCD program group.

WinCD MENU OVERVIEW

In this overview, menu selections are shown in **Bold Type**, dialog panel names are shown in *Italics*, and dialog panel entries or choices are shown in Ordinary Type. Like all Windows menus, WinCD menus are arranged hierarchically. For example, to get to the *ASCII File Information panel*, you must choose **File** from the main menu, **Open** from the secondary menu, and complete the operations required by the *Input File* panel. All menu selections can be made either by clicking and releasing the left mouse button with the cursor on the menu selection, or from the keyboard by holding down the ALT key and pressing the letter that is underlined in the desired menu selection. This overview is intended to give you a quick look at WinCD capabilities. The next section provides much greater detail on each menu and dialog panel in WinCD.

File
- **Open**
  - *Input File*
    - Select File & Directory
  - *ASCII File Information*
    - Starting Date
    - Starting Time
    - Epoch Duration
      - Units
      - Multiplier
    - Column
    - Detrend on Input
    - Set Data Mod 1000
- **Save**
  - *Saving Data From:*
    - Epoch by Epoch
      - Epoch Number
      - Raw Data
      - Detrended Data
      - Remodulate
      - Residuals
      - Phase
      - Amplitude
      - Trend
    - Trim Output
      - Start Epoch
      - End Epoch
    - Retrend the Remoduate
    - Append Column to File
      - File Name
- **Save As**
  - *Output File*
    - Select File & Directory
- **Print Screen**
- **Batch Processing**
  - **Execute Batch Job**
    - *CD -- Batch Processing*
      - Select Index File & Directory
      - Select Parameter File & Directory

Create Parameter File

Create CD Parameter File for Batch Processing

Specify data characteristics

Specify output file name

Specify data to save to output file

Create Index File

[not implemented yet]

Batch Processing Help

CD

CD Parameters

Epochs in Base Period	Fold-out
Cycles per Base Period	Gain
Use Residuals	Line Color
Detrend Options	Filter [not implemented]

Display

Clear	**Residuals**
Raw Data	**Amplitude**
Detrended Data	**Phase**
Linear Trend	**Time Reference**
Remodulate	

View

Epoch-by-Epoch Data

View Data on Screen

Epoch Number	Residuals
Raw Data	Amplitude
Detrended Data	Phase
Remodulate	Trend
Retrend the Remodulate	

Statistics

File Statistics

Peaks, Valleys, Zero Crossings

Options

Zoom

Adjust Data Analysis Window

Start Epoch

End Epoch

Smooth

Sliding Average

Sliding Window Size

Pool

Number of Epochs to Pool

Set Colors

Background

Foreground

Plotting

About

About CD

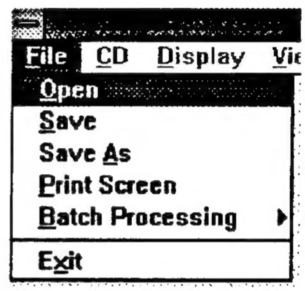
WINCD MENU DETAILS

MAIN MENU

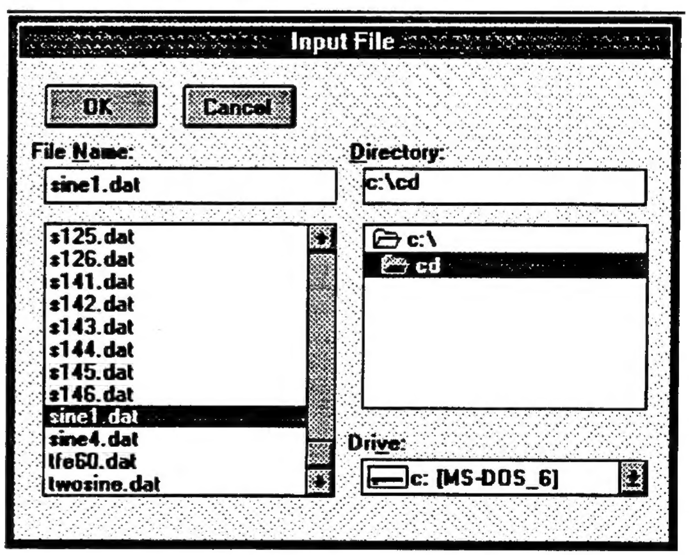
WinCD uses standard conventional Windows drop-down menus for access to program features. The Main Menu is used to initiate all operations in WinCD. When the program is first started, some of the choices will be "grayed", indicating that they are not available at that time. Unavailable options at start-up include CD, Display, and View. This is because until a file is loaded into WinCD, there are no data on which these options can operate. Once a file has been loaded, all options on the main menu become active. When you encounter other grayed options on WinCD menus, this means some essential prerequisite operation must be carried out before the option becomes active. Throughout WinCD menus, each menu choice has one underlined letter which indicates that the selection can be activated without the mouse by holding down the ALT key and typing the letter.

MAIN MENU: FILE

File: Open

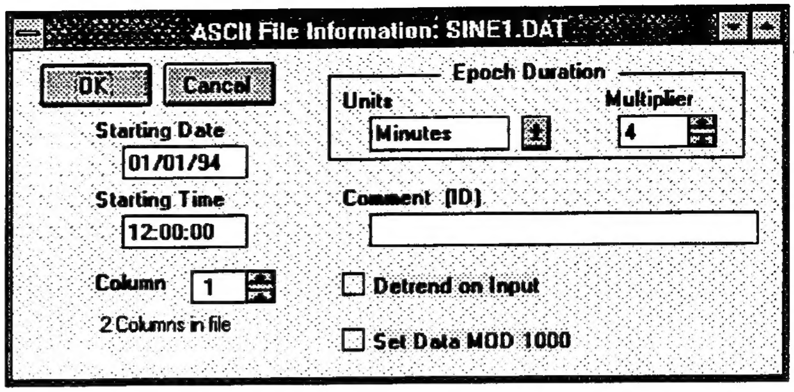


"Open" is used to read data files into WinCD. Selecting **Open** from the File menu will bring up the Input File dialog panel that allows you to select a data file from any device or directory on your system.

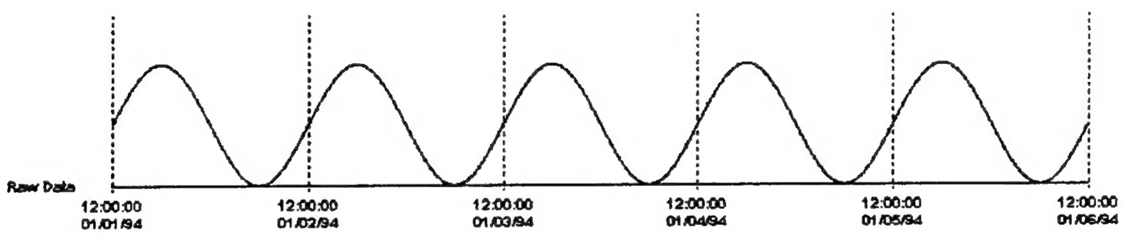


The *Input File* dialog works like all other Windows dialog panels, allowing you to set the Drive, Directory, and File you want to analyze with WinCD. Changing the directory or drive automatically changes the files that are displayed in the file list box. Clicking once on a file name causes it to appear in the File Name box. If you double-click on a file name, or click the OK button, WinCD will immediately begin processing that file. You can back out of this form any time by clicking on Cancel. WinCD expects "DAT" to be the file type for data files, although other file types will be accepted. The important thing is that the data within the file must be arranged properly. In this example, the file "SINE1.DAT" has been selected. This is a fake data file containing 1800 rows and two columns of numbers. WinCD accepts spaces, tabs, and commas as separators between columns. The data in column 1 of "SINE1.DAT" represent 5 replications of a sine wave with a peak-to-peak amplitude of 2000 and a mean of 1000. This time series will be used to illustrate the features of WinCD.

WinCD accepts two kinds of files, plain text (ASCII) files in which time series are arranged in columns, and actigraph files, generated from wrist-worn activity monitors manufactured by Precision Control Design, Inc. Most applications will use ASCII files.



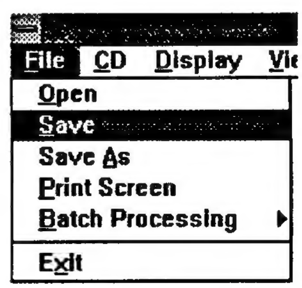
After the *Input File* dialog panel is closed by clicking OK, if the selected file is an ASCII (i.e. plain text) file, the *ASCII File Information* dialog panel will appear. This dialog requires you to enter critical information about the file so WinCD can process it properly. WinCD uses Starting Date and Starting Time to label the graphs and displays generated by the program. In the event the data file contains more than one column of data, Column is used to select which column is to be analyzed. Epoch Duration refers to the interval between observations. This value is set by adjusting the Units and Multiplier by clicking on the scrolling arrows at the right of the boxes. To process our sample file, "SINE1.DAT," We have set the starting date to 1/1/94, and the starting time to 12:00:00. Since this file contains 360 epochs per cycle, we have set the epoch duration to 4 minutes (360 x 4 = 1440, the number of minutes in one day). The Comment field provides text which will appear in a panel on the status bar at the bottom of the main screen. Clicking Detrend on Input will cause the mean of the data set to be subtracted from the value for each epoch, at the time the data are read in. This option is useful when the mean of the data set is large relative to the variability of the data set, as is usually the case for body temperature data. Finally "Set Data Mod 1000" should be checked when values over 1000 were used to mark special events in the data, and will result in the truncation of data to the remainder after the values are divided by 1000. This may be necessary for some actigraph data, but normally it should remain unchecked.



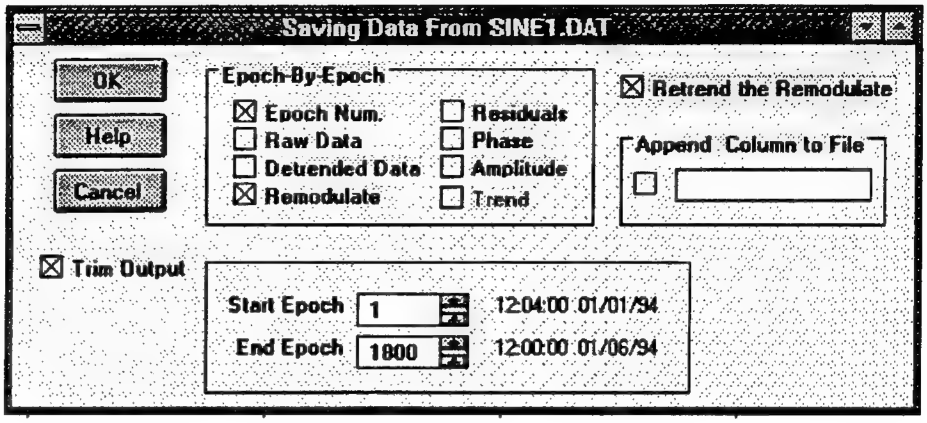
After OK is clicked on the *ASCII File Information* panel, WinCD reads in the data and plots the raw data on the screen. The horizontal axis of the graph is labeled with the time and date, and the file name appears both in the screen header and in the informational panel at the bottom of the screen.

File: Save

This selection is used to save the results of a CD operation in an output file. When it is selected the *Save Data to File* dialog panel will appear, allowing specification of what data to save, and how it is to be saved.



WinCD saves data in an epoch-by-epoch manner. The eight check boxes in the Epoch-By Epoch frame specify the elements that may be saved in the data file. The "Retrend the Remodulate" check box will result in addition of either the mean of the time series or the linear trend (depending on the "Detrending" method used in performing the CD-- see "CD Parameters" dialog below) to the remodulate prior to saving the data. Normally, the data are saved as "filename.CDX" where "filename" is the name of the original data file (e.g. "filename.DAT"). If the "Append Column to File" box is checked, rather than creating a new file, new columns will be added to the specified output file. WinCD saves the name of the last file to be output in this box. The user also has the option of typing in a new name, for example "GROUP1.CDX". If the file does not exist it will be created. This option allows the user to compile a database containing results of multiple CD analyses, for example, for a single subject on different days, or for pooling different subjects in an experiment. Finally, the Trim Output check box allows the user to set starting and ending epochs for the output file. This option enables selection of a subset of the data for output. Using this feature, for example, the user could output only one day of a multiday file (see sample analysis of "TFE60.DAT").



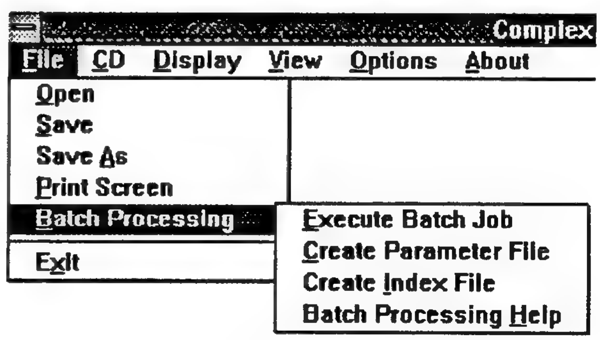
File: Save As

This selection operates exactly like the Save selection, except it calls up a dialog panel that allows you to specify a file name for the output after the *Save Data to File* dialog is completed.

File: Print Screen

This selection will print the current screen on the printer that is installed as the Windows printer.

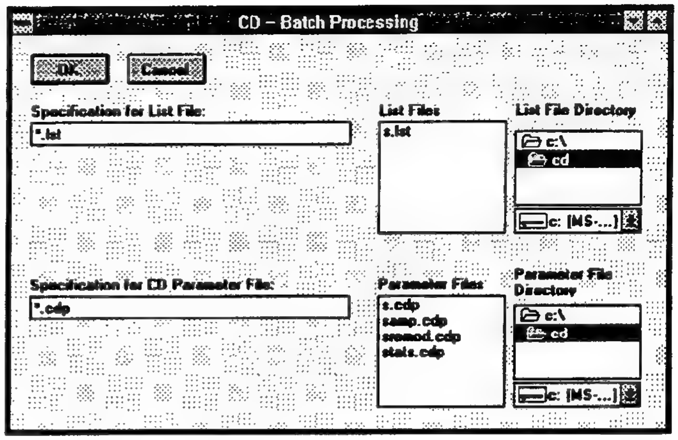
File: Batch Processing



This selection provides the capability to process a number of data files at the same time, specified in a List File, according to parameters specified in a Parameter File. Thus, for example, data files generated for all of the subjects in an experiment could be processed at one time with the same set of CD parameters. Rhythmic activities, such as circadian rhythms in body temperature and task performances, are highly individualistic. The local times when body temperature reaches peak and trough values are highly consistent within each individual, but may differ significantly from one individual to another. In spite of these inter-individual differences, the peak and trough times of a group of normal human beings cluster in a narrowly defined time range. In fact, Franz Halberg and his colleagues, in performing "cosinor" analyses, stress the importance of obtaining such inter-subject agreement in defining the existence of a biological rhythm.

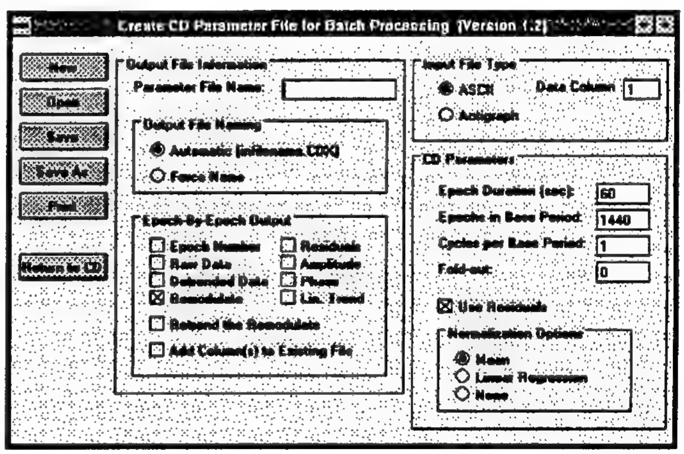
The analysis of group data requires repetition of the same CD analysis on the time series of many subjects. WinCD offers batch processing to ease repeated application of the same CD parameters. In batch processing, the names of all data files selected for analysis are listed in a computer file, and each of these listed files will be processed one at a time against a file that specifies the CD analysis parameters. Examples of such files are provided as S.LST and SREMOD.CDP in conjunction with analysis of the 12 files named SXXX.DAT (i.e. S121, S122, etc.; described on page 19 of this manual).

File: Batch Processing: Execute Batch Job



This selection brings up a dialog panel for specification of two files to control the batch job. First, an ASCII List File which contains the names of the files to process is required. This file must have the file type "LST". The second file is a Parameter File, which specifies the parameters to be used by WinCD in processing the files, the name of the output file, and what data to be saved in the output file. This file can be constructed by selecting the second choice on the **Batch Processing** sub-menu.

File: Batch Processing: Create Parameter File



This dialog allows you to create and / or modify parameter files for batch processing. These parameters will be used to process all of the files specified in the "LST" file for the job. Most of the items on this dialog should be self-explanatory, but Force Name requires some additional explanation. If this selection is made, the user must enter a name to be used for the output of WinCD. However, the same name will be used for all of the files in the job, and thus the data for each file will overwrite that for the previous file unless Add Column(s) to Existing File is also checked. Users are also cautioned that if data from several files are combined in this manner, all of the files *must* contain the same number of epochs, or unpredictable (and probably unusable) results will occur.

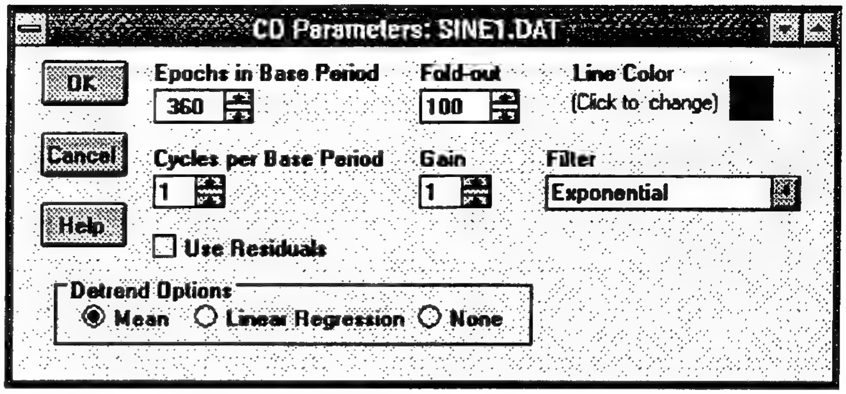
File: Batch Processing: Create Index File

This option is not yet implemented in WinCD, Version 1.0. Use a text editor such as the Windows Notepad to create an ASCII list of files to process, with one file name per line. Do *not* use a word processor such as Microsoft Word or Word Perfect to create this file since these programs introduce non-printing charcters into the file. The Index File must have a file type of "LST", e.g. MYLIST.LST.

File: Batch Processing: Help

This option will bring up a screen of information about WinCD Batch Processing.

MAIN MENU: CD



Selecting this option from the Main Menu brings up the *CD Parameters* dialog panel, which is the heart of WinCD. WinCD defines a "Base Period" as the period of primary interest. For example, if circadian rhythms are the focus, 24 hours is the Base Period. When a data file is loaded into WinCD, The Epochs in Base Period is set to a value that assumes a Base Period of 24 hours, and Cycles per Base Period is set to 1. These default values will automatically extract the 24-hour (i.e. "Circadian") frequency from the time series. Other frequencies may be analyzed by changing either of these two values by either entering new values from the keyboard, or by using the scrolling arrows at the right of the text boxes.

Detrend Options refers to the procedure used by WinCD to normalize the data prior to the actual CD calculations. Mean subtracts the mean of the time series from each data point. In electronic terms, it eliminates the "DC" component from the wave form. Linear Regression performs a linear regression of the entire time series and subtracts the value of that function at each epoch from the data for that epoch. Both options result in a detrended time series with a mean of zero, which WinCD requires for its filtering operation. Obviously, None means what it says -- no normalization is performed. Normally, either Mean or Linear Regression should be chosen when performing the first CD on a given time series. Once a CD has been performed, WinCD will automatically switch this option to None.

Use Residuals has no effect on the first CD on a given time series, but directs WinCD to operate on the residuals derived from subtracting the previous remodulate from either: a) the detrended time series if this is the second CD on this time series; or b) from the accumulated residuals if this is the third or greater CD on this time series. Use Residuals is used when doing repetitive CD's on the same time series at different frequencies (i.e. different settings of Cycles per Base Period), thus assessing the contribution of different frequencies to the original time series.

Fold-out refers to a technique that is used by WinCD to minimize distortions in the CD process by the beginning and end of a time series. This is extrapolation process in which the ends of the time series are projected in time. Assume a fold-out of 100 points. If you imagine the first data point as a hinge, WinCD folds out the first 100 by swinging them around the first point such that each point in the folded-out section is paired to a point in the original time series. For example, the first folded out point (-1) is paired with the first point in the original time series (1), point -2 is paired with point 2, and so on. In the following example, the first 4 numbers of the original time series are 5, 9, 6, 7, indicated by bold numerals, and the first 3 numbers are folded out, indicated by italics:

folded-out time series: *4* *1* *5* **5** **9** **6** **7** ...

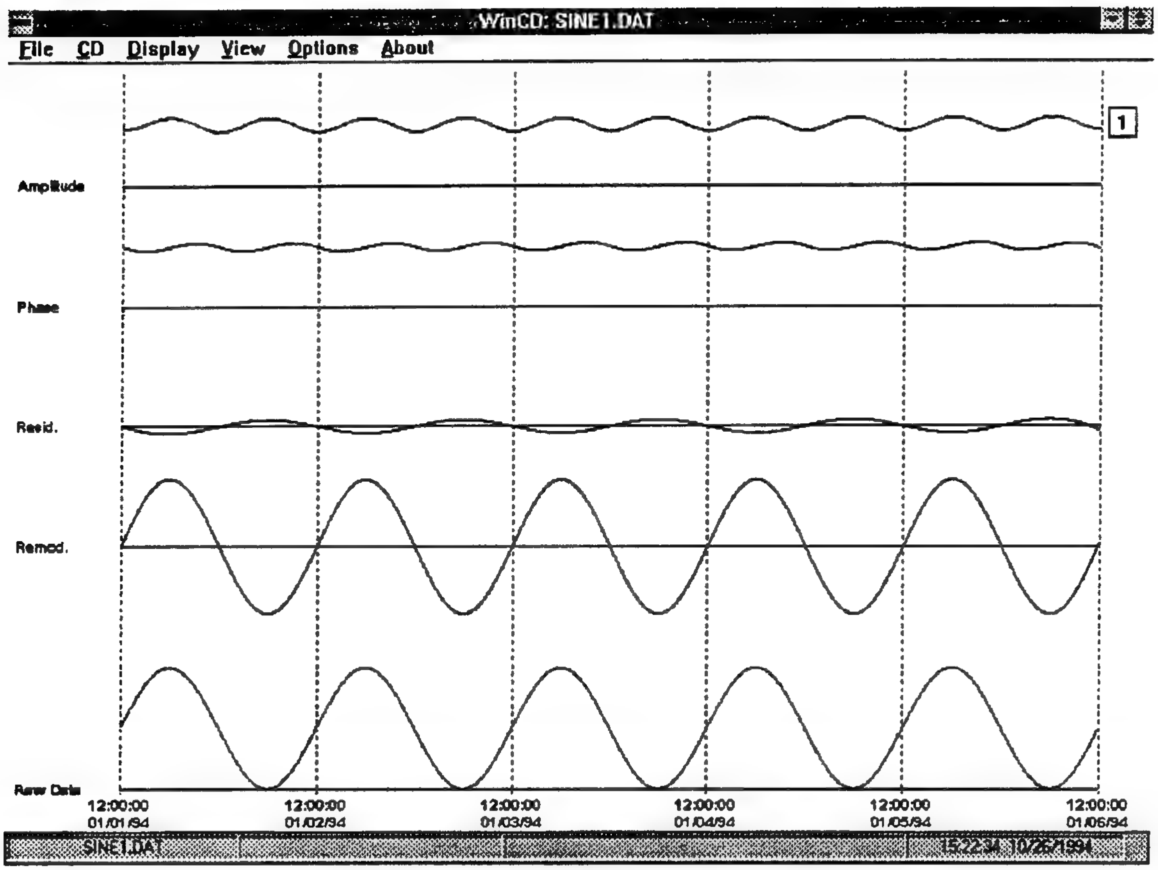
The general formula is:

$$F_n = O_1 - (O_n - O_1)$$

where F_n indicates folded-out values, O_1 is the first value of the time series, and O_n indicates values from the original time series. A similar procedure is used at the end of the time series.

The Gain value generally has little influence on the CD results. It must be a value from 0.1 to 1.0.

WinCD sets the color of the line used to plot the CD results to certain values, controlled by the setting of Cycles per Base Period. However, this value may be changed by clicking on the color box in the upper right corner of the *CD Parameters* panel. This will bring up a palette from which a new color may be selected.

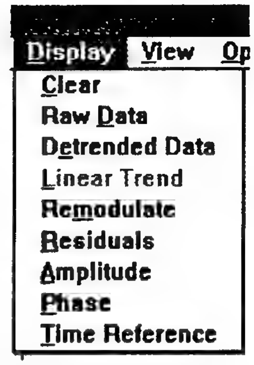


When OK is clicked on the *CD Parameters* panel, WinCD executes the complex demodulation process. As the computations progress, an informational box on the screen will display the steps in the CD process. When it is finished, the remodulate value will automatically be plotted above the raw data on the screen. Several additional plots are available using the Display option (see next section). This screen shows the Amplitude, Phase, and Residual plots for the "SINE1.DAT" data file after complex demodulation at the 24-hour frequency. Along the right margin, WinCD supplies a legend showing the epochs per base period and plotting colors for each successive CD performed on a data file.

A status bar containing four panels appears at the bottom of the WinCD screen. The first panel shows the current file name along with the column number if it is other than the first column, indicated by :Cx, where "x" is the column number, and any smoothing information indicated by :Pn or :Sn for pooling and sliding averages, where "n" is the number of epochs used for pooling or averaging. The second panel displays the file ID that was entered in the *ASCII File Information* panel, or the ID in the header of an actigraph file. Information about the raw data for individual epochs may be displayed in the third panel by clicking anywhere within the raw data display. This causes a small carat sign to appear below the raw

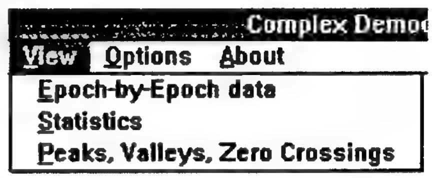
data baseline, and the epoch number, time, date, and raw data value for that epoch. Clicking anywhere outside the raw data display erases this information. Finally, the rightmost panel displays the current time and date.

MAIN MENU: Display



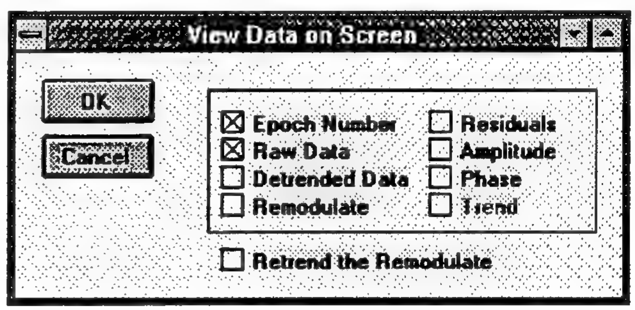
This option determines what information is displayed on the screen. **Clear** erases all information on the display. **Raw Data** displays the raw data and the time reference information. These items are automatically displayed when a data file is loaded, but occasionally it may be necessary to redisplay them after the screen is cleared. The **Remodulate** is automatically plotted at the completion of each CD. If multiple CD's are performed on a time series, a different color is used for each plot, and the color is indicated in the legend at the right of the screen by printing the Cycles per Base Period in the color used to plot the results of the CD. **Detrended Data** and **Residuals** are displayed above the remodulate on the same baseline to facilitate comparison. The detrended time series is plotted in a light color to distinguish it from the residual plot. **Amplitude** and **Phase** are plotted separately at the top of the screen.

MAIN MENU: View



This option enables on-screen viewing of numerical results of CD operations in several different ways.

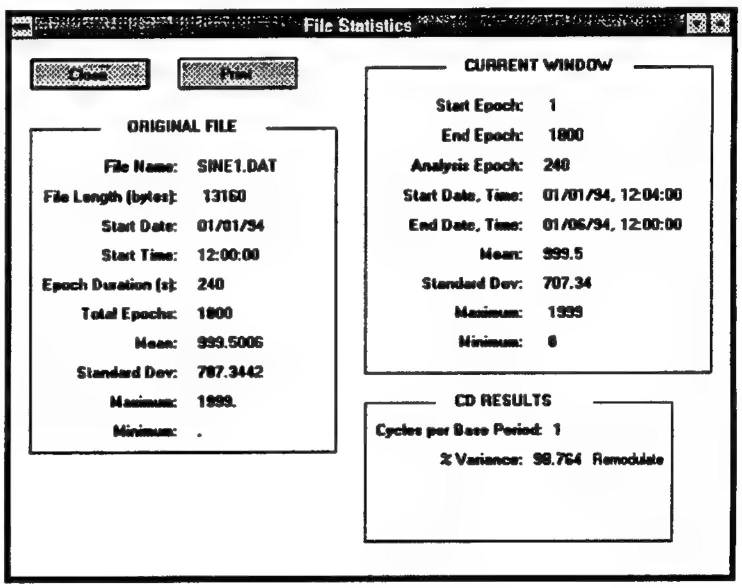
The "**Epoch-by-Epoch** choice brings up the *View Data on Screen* panel with check boxes for each of the data items that can be displayed on an epoch-by-epoch basis.



The selected data items are displayed 35 epochs at a time in a text box as shown to the right. Additional epochs, up to a maximum of 500, may be viewed by using the scroll bar at the right of the box. If the time series contains more than 500 epochs, the next "page" of epochs may be viewed by clicking the right mouse button anywhere on the text box. Previous pages can be recalled by holding down the Shift key while clicking the right mouse button. The text box can be erased at any time by double-clicking the mouse anywhere within the text box.

Epoch	Raw Data	Detrend	Remodulate	Residuals	Amplitude	Phase
1	1017.0000	17.4995	7.0882	10.4113	948.7060	199.1498
2	1034.0000	34.4995	27.8045	6.6949	947.6922	198.6375
3	1052.0000	52.4995	48.4623	4.0372	946.8536	198.1324
4	1069.0000	69.4995	69.0564	.4431	946.1892	197.6292
5	1087.0000	87.4995	89.5018	-2.0024	945.6976	197.1289
6	1104.0000	104.4995	110.0336	-5.5341	945.3775	196.6323
7	1121.0000	121.4995	130.4066	-8.9072	945.2269	196.1400
8	1139.0000	139.4995	150.6960	-11.1966	945.2439	195.6529
9	1156.0000	156.4995	170.8968	-14.3973	945.4261	195.1717
10	1173.0000	173.4995	191.0039	-17.5045	945.7713	194.6973
11	1190.0000	190.4995	211.0125	-20.5131	946.2766	194.2303
12	1207.0000	207.4995	230.9176	-23.4182	946.9390	193.7714
13	1224.0000	224.4995	250.7143	-26.2148	947.7554	193.3214
14	1241.0000	241.4995	270.3976	-28.8982	948.7227	192.8808
15	1258.0000	258.4995	289.9628	-31.4634	949.8378	192.4504
16	1275.0000	275.4995	309.4049	-33.9055	951.0948	192.0307
17	1292.0000	292.4995	328.7191	-36.2197	952.4922	191.6224
18	1309.0000	309.4995	347.9006	-38.4012	954.0251	191.2259
19	1325.0000	325.4995	366.9446	-41.4451	955.6894	190.8419
20	1342.0000	342.4995	385.8462	-43.3468	957.4806	190.4707
21	1358.0000	358.4995	404.6009	-46.1014	959.3943	190.1129
22	1374.0000	374.4995	423.2037	-48.7043	961.4260	189.7688
23	1390.0000	390.4995	441.6502	-51.1507	963.5707	189.4390
24	1406.0000	406.4995	459.9355	-53.4361	965.8239	189.1236
25	1422.0000	422.4995	478.0551	-55.5557	968.1804	188.8231
26	1438.0000	438.4995	496.0044	-57.5049	970.6355	188.5377
27	1453.0000	453.4995	513.7700	-60.2794	973.1840	188.2678
28	1469.0000	469.4995	531.3738	-61.8743	975.8207	188.0135
29	1484.0000	484.4995	548.7849	-64.2854	978.5406	187.7750
30	1499.0000	499.4995	566.0076	-66.5081	981.3385	187.5528
31	1515.0000	515.4995	583.0376	-67.5381	984.2091	187.3461
32	1529.0000	529.4995	599.8704	-70.3710	987.1472	187.1560
33	1544.0000	544.4995	616.5018	-72.0024	990.1473	186.9822
34	1559.0000	559.4995	632.9274	-73.4280	993.2045	186.8247
35	1573.0000	573.4995	649.1431	-75.6437	996.3134	186.6836

Choosing Statistics displays a panel with various statistics on the currently loaded data file. Separate frames are included for the original file and the CURRENT WINDOW (see Options: Zoom in the next section). If a CD has been performed, the percentage of variance accounted for by the remodulate is also shown. This value is obtained by the following formula:



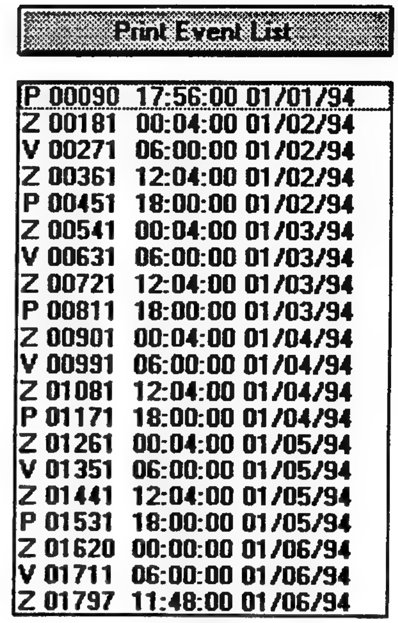
$$\%vac = 100 \times (1 - vRes / vRaw)$$

where vRes = variance of the residuals and vRaw = variance of the original time series. If multiple CD's have been performed the % variance accounted for reflects the cumulative effects of all CD's performed on the time series. If the "Linear Regression" option was selected, the amount of the variance in the original time series accounted for by the linear trend is also shown, as well as the equation of the linear regression function. The formula for computing the variance accounted for by the linear trend is:

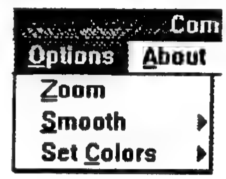
$$\%vac = 100 \times (1 - vDet / vRaw)$$

Where vDet is the variance of the detrended time series. The panel can be printed on the system printer by clicking **Print**, and **Cancel** erases the panel.

Choosing **Peaks, Valleys, Zero Crossings** displays a table or "Event List" showing the epoch numbers and times when the remodulate reaches a maximum, minimum, or crosses zero. This list can be printed by clicking on the Print Event List button or erased by double-clicking anywhere on the list.

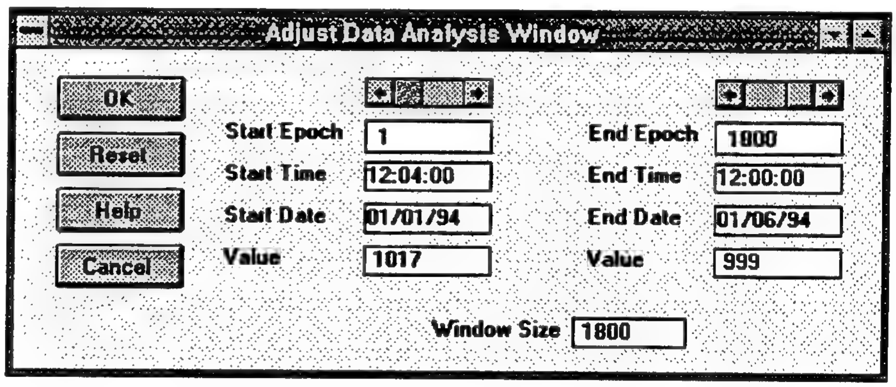


MAIN MENU: Options



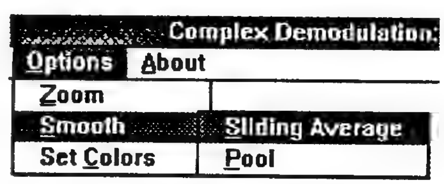
This selection allows setting of miscellaneous options for data editing and display.

Options: Zoom

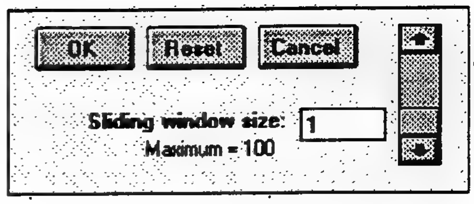


Zoom brings up the *Adjust Data Analysis Window* panel which allows the user to set the starting and ending epochs for analysis. In doing the next CD analysis, WinCD will ignore epochs that precede the new start epoch and follow the new end epoch. The values for new start and end epochs may be adjusted using the horizontal scroll bars or by directly entering new values into the Start Epoch and End Epoch text boxes. Clicking the **Reset** button restores the original settings.

Options: Smooth



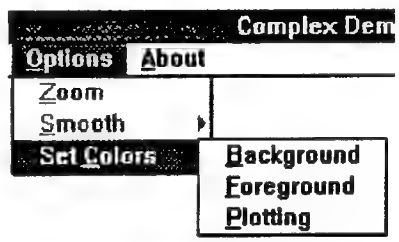
Often a time series is contaminated with measurement errors or "noise" so much that any underlying smooth rhythmic oscillations are masked. **Smooth** provides two methods for combining data from adjacent epochs in order to minimize the effects of rapid fluctuations in the data. Smoothing is particularly useful when values may fluctuate rapidly from epoch to epoch. Such fluctuation may be most likely when the epoch duration is relatively short. Thus **Smooth** options integrate the data over larger periods of time.



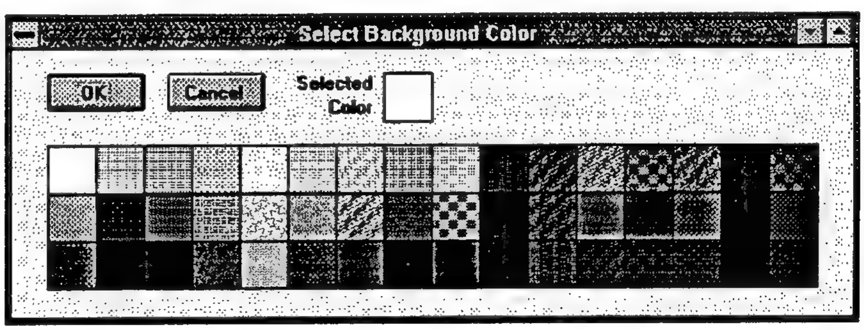
The **Sliding Average** smoothes data by averaging adjacent epochs in the raw data. This option brings up a panel to set the size of the sliding window by either entering the number of epochs for the window directly or by using the scroll bar. clicking Reset sets the sliding window size back to 1 (i.e. restores the original data). When OK is clicked, WinCD smoothes the data by averaging adjacent epochs. For example, for a data window of 5, the values of the first, second, third, fourth and fifth data points of the original time series will be averaged, and the average is placed at the middle (third) position of the original time series replacing the original value. Then, the second, third, fourth, fifth and sixth values are averaged, replacing the fourth value of the original time series. This process is repeated to the last data point. To handle data points at the beginning and end of the time series, the first and last points are used repetitively as necessary to construct the average. Thus, for example, the first point in the averaged time series with a window size of 5, is the average of 3 x value 1 plus value 2 plus value 3. Hence a smoothed time series, resulting from this "low-pass" filter, will retain the same number of data points as in the original.

The **Pool** option simply sums adjacent data points in the original time series. This option is handy when the data were sampled too frequently resulting in excessive epoch-to-epoch variability. For example, data collected in one-minute epochs can be collapsed into 10-minute or one-hour epochs. The size of the pooling window is set or changed with a panel similar to that for the sliding average option.

Options: Set Colors



WinCD normally sets the colors used for the display, but also allows the user to set the colors manually by selecting from a palette which is displayed on the *Select Color* panel.



Selecting any of these options brings up the palette. To select a color, simply click on the color, then click OK. **Background** sets the background color for the main screen and clears the screen. This option is particularly useful if you plan to print the screen. It is recommended that in this case you set the background to white prior to reading any data into WinCD. **Foreground** sets the color for displaying the axes, reference lines, axis labels, and raw data. **Plotting** sets the color used for plotting the Amplitude, Phase, and Remodulate.

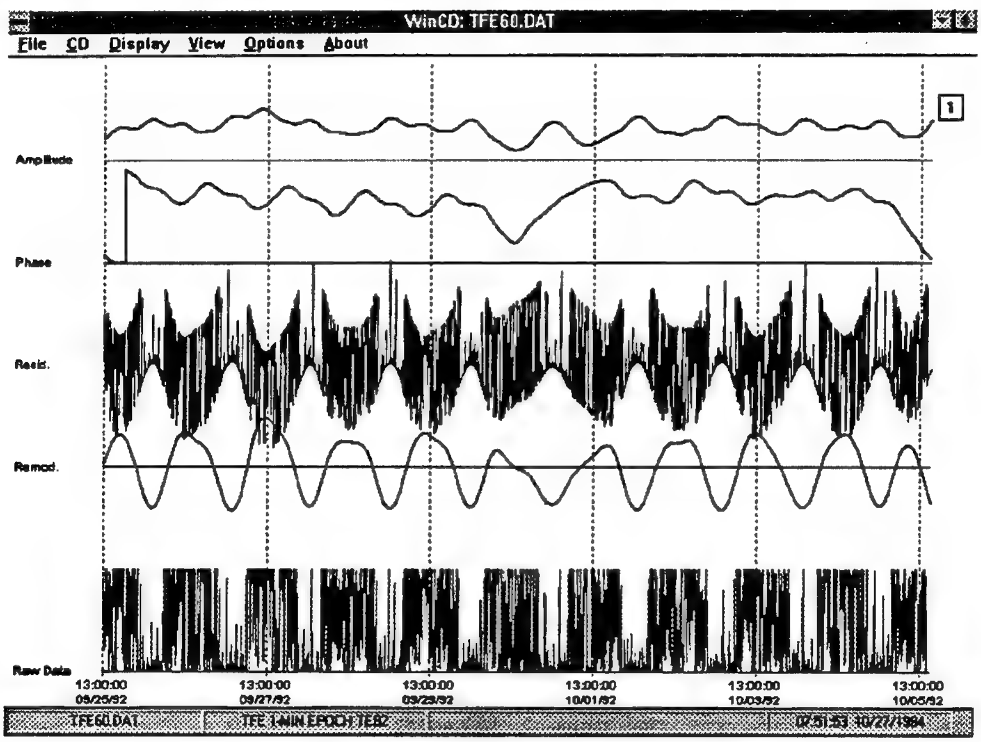
MAIN MENU: About

This option brings up a general informational screen concerning WinCD.

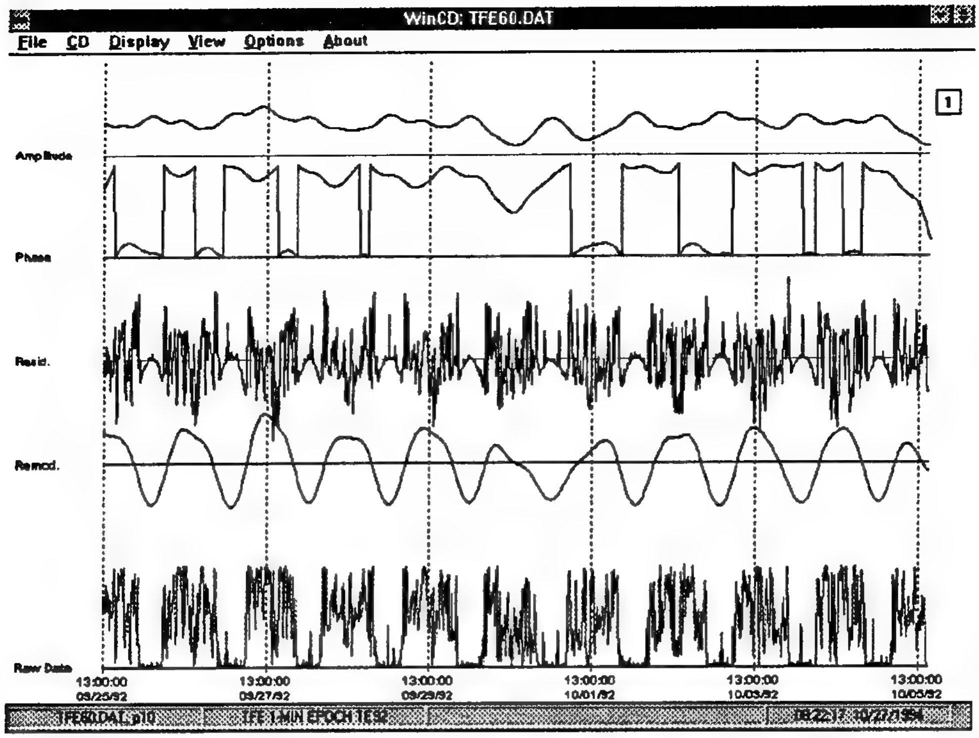
Examples of WinCD Applications

Analysis of Activity Data

Actigraphs may be programmed to sample and store activity in short epochs for long periods of time. Typically, 1-min epochs are used, resulting in 1440 samples per day. The file "TFE60.DAT" represents data sampled over slightly more than 10 days, and contains 14592 epochs. The file is read into WinCD using the normal **File: Open** choices from the main menu. Actigraphic data files include a header containing information regarding epoch duration, and starting and ending times and dates. Thus, the user is not required to enter these items. The following figure shows the screen after this file has been read in, a CD performed at 1 CPD, and **Display: Amplitude, Phase,** and **Residuals** options invoked. The plots show some changes in the remodulate waveform, amplitude, and phase on the fifth and sixth days. In fact, this subject was ill on these two days, and was home in bed much of the time.

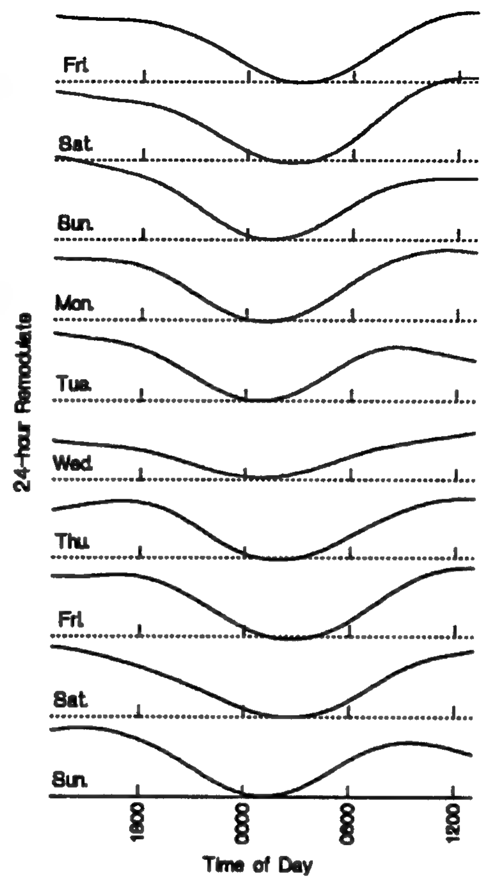


On some computers, processing a data file of this size would be quite slow, since WinCD processes the data one epoch at a time. With activity data, the number of calculations to be performed can be reduced substantially without significant loss of precision by pooling the data over larger time periods, effectively increasing the epoch size. The following figure shows the effects of pooling over 10 epochs (**Options: Smooth, Pool**).



In this file, increasing the epoch from 1 min to 10 min clearly reduced the variability of the raw data and the residuals, but had little effect on the amplitude and remodulate waveforms. Comparisons of the Peaks, Valleys and Zero Crossings of the remodulates from the 1 and 10 min epoch CD's shows that they match to within ± 10 min. The phase plot appears somewhat noisy. In fact, the apparent noise is due to the fact that the phase is hovering around zero degrees, thus the plot is bouncing back and forth between minimum (zero degrees) and maximum (360 degrees) values. This illustrates that the important thing to note about phase plots is not the absolute values, but the pattern of the phase waveform. Changing the analysis epoch from 1 min to 10 min did not materially affect the pattern of phase changes, which was disrupted in both cases on the fifth and sixth days. Pooling data functions as a low-pass filter, eliminating some of the high frequency components from the data. Thus, inspection of the file statistics screen (View: Statistics) shows that the remodulate accounts for 40.27% of the variance with one-min epochs and 51.73% of the variance with 10-min epochs.

The output options of WinCD can be used to customize output files for particular applications. For example, it may be desirable to statistically or graphically compare the data from different days. Selecting File: Save brings up a panel that allows a great deal of versatility in formatting an output file. Clicking Trim Output allows you to set the starting and ending epochs for data to be saved in the output file. In processing "TFE60.DAT," a multi-column output file with one column per day, "TFE60.CDX," can be constructed as follows:



1. Read in "TFE60.DAT" (**File: Open**)
2. Change epoch to 10 min (**Options: Smooth, Pool**)
3. Perform CD at one CPD (CD)
   - Epochs in Base Period: 144
   - Cycles per Base Period: 1
   - Detrend Options: Mean
   - Fold-out: 100
   - Gain: 1
4. Output remodulate for the first day (**File: Save**)
   - Check:
     - Remodulate
     - Retrend the Remodulate
     - Trim Output
       - Set Start Epoch: 1
       - Set End Epoch: 144
5. Output remodulate for days 2-10 (**File: Save**)
   - Check:
     - Remodulate
     - Retrend the Remodulate
     - Append Column to File
       (will add a column to "TFE60.CDX")
     - Trim Output
       - Set Start Epoch: 145, 289, 433, ... (for days 2, 3, 4 ...and so forth)
       - Set End Epoch: 288, 432, 576, ...

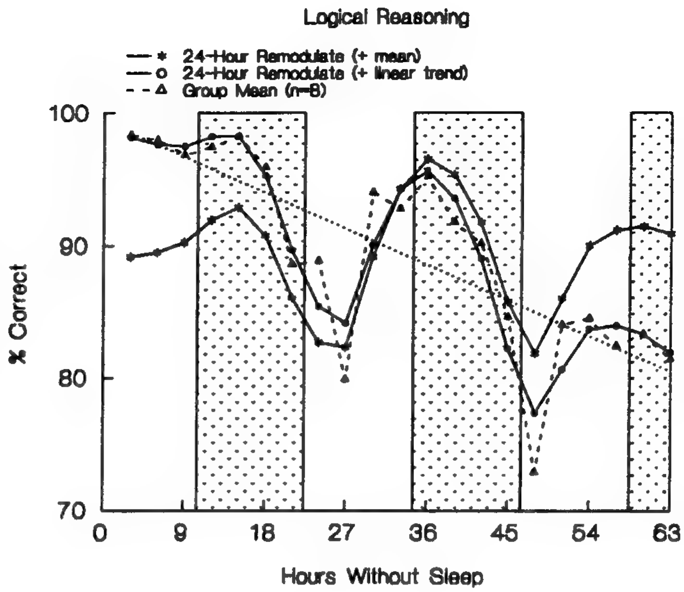
This sequence of steps will result in an output file with 10 columns (one for each day) and 144 rows (one for each 10-min epoch). This file was used in conjunction with a graphics program to generate the previous figure, which allows detailed comparison of remodulate waveforms from each day of the 10-day data sample.

Separating Rhythms From Trends

In many situations, the dependent variable many be expected to change in a nonrhythmic manner over the course of an experiment. Examples include decreases in performance as a result of cumulative fatigue, or improvements in performance as a result of learning. WinCD can separate linear trends from rhythmic changes. The data file "LOG3AVG.DAT" contains the average accuracy scores of a group of 8 subjects

on a logical reasoning task. These data were collected as part of studies conducted at the Naval Health Research Center.[1]

These data were taken from a "Logical Reasoning" task that required the subject to respond to a set of logical problems by indicating whether a set of logical statements was true or false. For example, the subject might be presented with the statements "A does not follow B" and "B follows C, " and the string "ACB" on a computer screen. The subject then pressed "T" on the computer keyboard if he thought both statements were true or "F" if one or both of them was false. These tests were given as part of a performance assessment battery administered once every 3 hr during a 64-hr period of total sleep deprivation. In the figure, the times from 1800 hours to 0600 hours are shaded. The raw data, shown in the figure with triangles connected by dashed lines, showed a pronounced decline over the sleep deprivation period, with a clear dip in the early morning.



The steps used in performing the CD and saving the data for this figure include:

1. Read in "LOG3AVG.DAT" (**File: Open**)
   Set file parameters in *ASCII File Information* panel
      Unit: Hours
      Multiplier: 3
2. Perform CD at one CPD (CD)
   Epochs in Base Period: 8
   Cycles per Base Period: 1
   Detrend Options: Linear Regression
   Fold-out: 2
   Gain: 1
3. Save the Epoch Number, Raw Data, Remodulate, and Linear trend in "LOG3AVG.CDX" (**File: Save**)
   Check:
      Epoch number
      Raw data
      Remodulate
      Trend
4. Append the Retrended Remodulate to "LOG3AVG.CDX" (**File: Save [again]**)
   Uncheck:
      Epoch number
      Trend

[1] Thanks are expressed to Dr. Tamsin Kelly for permission to use these data that were selected from control subjects in studies of the effectiveness of naps and stimulants in reversing or preventing performance decrements during sleep deprivation.

Check:

Retrend the remodulate
Append column to file

5. Determine the mean of the time series from the *Statistics* panel (**View: Statistics**)

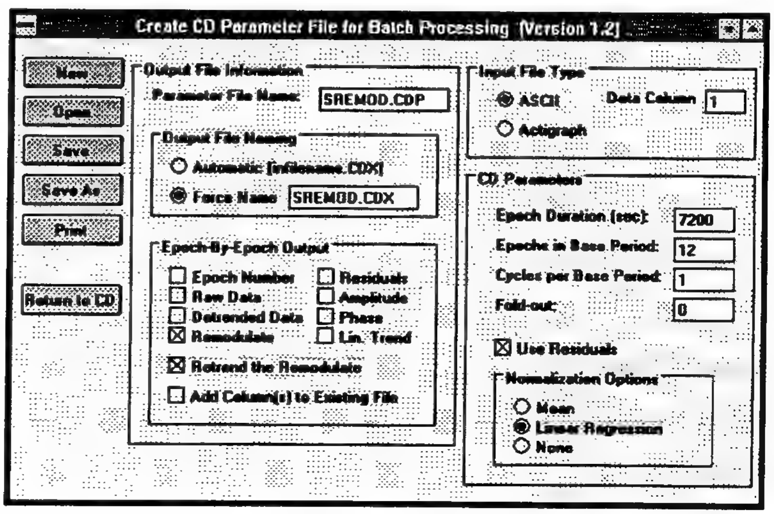
When these operations are complete, "LOG3AVG.CDX" will contain the information necessary to plot the raw data, linear trend, and 24-hr remodulate + linear trend. To plot the remodulate + mean, the mean (determined in step 5 above) must be added to the remodulate outside of WinCD. Alternatively, the CD process could be repeated using Mean as the detrending option, and a column containing the retrended remodulate appended to "LOG3AVG.CDX". The remodulate values (prior to retrending) obtained by this method, however, may differ slightly from those obtained using Linear Regression detrending.

The *Statistics* panel contains information on the amount of variance accounted for by the linear trend and the remodulate. In the case of "LOG3AVG", the linear trend accounted for 59.3% of the variance in the original time series, and the 24-hour remodulate accounted for 90.93% of the remaining (i.e. non-linear) variance.

Batch Processing

The data in this example were collected in a study performed at the Defence and Civil Institute of Environmental Medicine of Canada[2]. In this experiment, volunteers were tested on a battery of tests every two hours during 64 hr of total sleep deprivation. One of the tests was a "synthetic work task" (Elsmore, 1994) requiring the subjects to simultaneously perform four different tasks simulating a watch-standing job. One of the measures derived from this task is a "composite score" which reflects overall efficiency on the task. In this example, the remodulate and amplitude of the 24-hour rhythm in composite score for each subject were derived and pooled to yield group curves for these variables.

The data to be analyzed are in the 12 data files "SXXX.DAT," where XXX represents the subject number. Each time series contains scores from 36 test sessions, with the first three sessions being practice sessions prior to sleep deprivation, sessions 4 to 33 conducted at 2-hr intervals with no sleep, and the last three, recovery sessions following a period of sleep. Batch processing requires two files to describe the analysis task. The first, an "index file" is an ASCII file containing the file names to be analyzed. The file "S.LST" was used in this example.



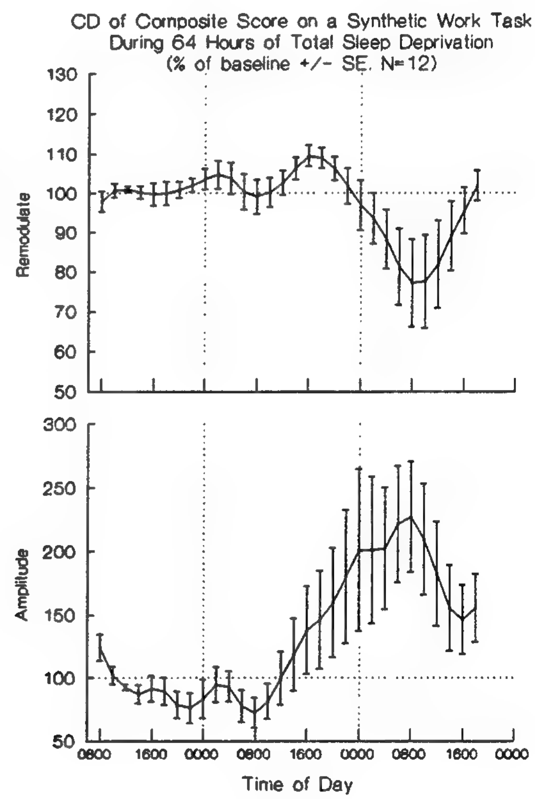
The second file required is a "parameter file" which is generated from within WinCD by selecting **File: Batch Processing: Create Parameter File.** The parameter file panel for the analysis of the 24-hour component is shown to the right. New resets all options to their default values. Open is used to read in existing parameter files, Save saves the parameter files with the specified name, Save As brings up a conventional File dialog panel which allows you to change

[2] Thanks are expressed to Dr. Ross Pigeau for permission to use these data which were collected in a study of the efficacy of the drug modafinil.

the name and location of the output file, Print prints a text version of the parameters on the system printer, and Return to CD exits from this routine.

To do the present analysis, the Force Name option was selected, and the name "SREMOD.CDX" entered into the text box. This will cause all output to go into this file. Since Add Column(s) to Existing File is checked, the data from each file will be appended as a new column to the output file. Only one item, Remodulate is checked for epoch-by-epoch output. Retrend the Remodulate directs WinCD to add the linear trend to the remodulate prior to writing it to the output file. Epoch Duration is set to 7200 (2 hr.), and there are 12 Epochs per Base Period (i.e. 24 hr.), and we are interested in the base period so Cycles per Base Period is set to 1. Linear Regression was selected since it is not unusual in this sort of experiment for performance to decline systematically over the course of the experiment. Finally, the input file is an ASCII file, and there is only 1 column in each file. When all the parameters are set properly, clicking OK launches the batch job. When the job is finished, "SREMOD.CDX" will contain 12 columns of 36 numbers, and normal WinCD operations will be resumed.

The top frame of this figure was generated from the data in "SREMOD.CDX" using a statistical program (SYSTAT) to average the columns, compute the standard errors of the mean, and plot the results, omitting the first three (practice) and last three (recovery) sessions. The data in the bottom frame were generated in a similar manner using the amplitude of the 24-hr component rather than the remodulate (see "SAMP.CDP").



Parting Comment

These examples were intended to give a feel for the capabilities of WinCD, and to illustrate some of the program's features. WinCD is unique among time-series analysis programs in that it enables the user to engage in exploratory data analysis in the time-series domain. Please feel free to communicate your comments to the author. Enjoy!

Further Readings

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APPENDIX 1

Complex Demodulation Explained

Complex demodulation (CD) was invented by econometricians specifically to study nonstationary time series. Stationarity is a requirement of spectral and curve-fitting techniques, which expect frequencies, amplitudes and phases to remain constant over the period of observation. The goal of CD is to determine epoch by epoch estimates of the amplitude and phase of some sinusoidal waveform of interest. Such estimates can be used to recreate the waveform in a manner that reflects the changes in amplitude and phase, that is, nonstationarities, present in the original time series.

The "complex" in CD refers to the description of a waveform as having a real and an imaginary component. The real component represents the phase of the sinusoid of interest, and the imaginary component represents the amplitude. Since we know the frequency of interest, what remains to be determined are amplitudes and phases. A small side trip is needed to understand the role of "demodulation" in the CD process. When a waveform and a sinusoid are multiplied together, instant by instant, new frequencies are created. The results of multiplication are the original frequencies in the waveform, and all of the sum and difference frequencies formed by the components of the original waveform and the "modulating," or multiplying, sinusoid.

We concentrate on the difference frequencies in CD. If a component of the original waveform is at the frequency of the modulating sinusoid, then it has a difference frequency value at or near zero. A zero frequency value is a show-stopper for many people. It might help to think of it as a constant voltage (at zero) or a slowly varying voltage (near zero). The ability to take the information about some component of a complex signal and move it to a spectral position where we can manipulate it easily is at the heart of complex demodulation.

Our original signal was a single time series and, as indicated earlier, we wish to transform it into the complex domain, which has a real part and an imaginary part. The real and imaginary parts of a complex signal are orthogonal to one another, (i.e., their axes are at 90 degrees to one another). It is convenient that a cosine and a sine wave at the same frequency differ in phase by 90 degrees. The cosine wave is associated with the real part, and the sine wave is associated with the imaginary part in the complex domain. We can now bring the major pieces of CD together.

We create two modulated signals by multiplying the original time series first by the sine wave of interest and then again by multiplying the original time series by the cosine wave of interest. Remember, in each modulation operation we move information down into the vicinity of zero frequency, imaginary information in the sine modulation, and real information in the cosine modulation. The original components and their sum and difference components are still present in the modulated waveforms. All of these components are clutter that needs to be removed. Removal of the excess frequency clutter is accomplished through use of a low-pass filter that is located close to zero frequency. If the modulation operation is the heart of CD, this low pass filter is the brain. The behavior of the low pass filter that is used determines the overall performance of the complex demodulation operation. If the filter is very sharp and tight on the zero frequency, it will exclude more information that may lie near the frequency of interest. Such a tight filter will also have a long time delay characteristic and respond sluggishly to changes in the time series. The trade off between sharpness and time delay cannot be escaped. Choosing which trade-off to implement is a matter of taste and art. If your business is understanding the dynamics of a process, then it pays to loosen up the filter and shorten its response time. Low-pass filters come in many varieties and most are simple to implement. We have made choices that seem to work well in our applications.

The outputs of the low-pass filtering operation provide estimates of the real and imaginary values of our sought-after frequency component, one set for each epoch. The rest is simple trigonometry. Imagine

plotting the point described by the real and imaginary estimates in complex space. The distance from the origin of the plot to the point provides an estimate of the peak amplitude of desired signal for that epoch. The distance is calculated as the hypotenuse of a right triangle. The angle the hypotenuse makes with the X-axis of our plot is the estimate of the phase angle expressed in degrees by WinCD. The phase angle is calculated as the tangent of the ratio of the imaginary and real estimates.

The estimates of peak amplitude and phase angle of the sought-for frequency component are each useful in their own right. Amplitude estimates can be used in considerations of the relative importance of one frequency component of a waveform compared with that of others. In fact, if one calculated a reasonable number of CDs at frequency values spanning a range of interest, an estimate of an amplitude spectrum for each epoch in the time series could be created. Such spectra are a direct analog of the hardware methods of spectral analyses made in acoustics before the advent of the mini- and microcomputer.

The estimates of phase angle are often ignored, perhaps because we are not used to thinking of angles as a component of a rotating vector. The first thing of interest when examining a phase plot is systematic organization. The phase of a noise component (noise in the sense of random noise rather than unwanted signal, such as hum) in a signal is expected to be more or less random. If the phase plot is disorganized, it is a sure bet that the component being analyzed is noise. If the frequency of the demodulated signal is equal to the frequency of the component in the original signal, then the phase plot will be a line of zero slope. If the frequency of the demodulated signal is higher than that of the component in the original signal, then the slope of the phase plot will be positive and directly related to the phase difference. By the same reasoning, a lower CD frequency will yield a phase plot having a negative slope.

If more accurate estimates of frequency are required by your application and the components of your time series are more or less stable, you can use the phase angle plots to adjust the CD frequency and "home in on" the component of interest. Iteration of this sort is simple but time-consuming. Perhaps the frequency of your sought-after component is dynamic and the focus of interest. In this case, it might be worthwhile to work out the relationship between phase angle and frequency difference and to use that relationship to transform the frequency plot.

In our experience, most users of CD want to cut to the chase and look at the filtered waveform component. The three values that determine the instantaneous value of a sinusoidal signal are in hand, (e.g., the CD frequency, the estimated peak amplitude, and the estimated phase angle). These values are combined in a process known as remodulation to create a visualization of the filtered component over time. The remodulate waveform differs radically from that obtained by fitting a sine wave to a time series. If you fit a sine wave, you get a sine wave and single overall estimates of amplitude and phase. CD, as you have seen, produces multiple estimates of amplitude and phase and, through remodulation, uses them to reconstruct a waveform.

The remodulate waveform is a rich source of material for further analyses. One can estimate the times of peaks and troughs, calculate periods of interest and examine asymmetries in the waveform. The Fourier Theorem, which states that a complex waveform can be represented by the sum of a series of sinusoids, can be put to good use in understanding the structure of a time series. Earlier, we talked about doing multiple CDs across the putative spectrum of the waveform. Adding the remodulates of these CDs together at each epoch will progressively reconstruct the original waveform. It is a simple step to calculate the proportion of variance in the original waveform that is accounted for by single remodulates or any combination thereof.

We have deliberately chosen to keep the explanation of complex demodulation as simple as our powers of description permit. More mathematically rigorous explanations can be found in the bibliography. Our purpose is to provide you with a sense of how CD is done and what it might provide for you as a tool for uncovering and understanding the dynamics of time series you collect so laboriously. Complex demodulation is certainly not a panacea against the woes of time-series analysis but it is a remarkably useful tool. Perhaps its main virtues lie in fact that each step in the analysis can be visualized, and most,

in and of themselves, can yield useful information. The results are a source of material for further statistical analysis. Finally, we have found over the years that if one exercises restraint, the results of CD are readily communicated to audiences.

APPENDIX 2

Glossary

Actigraph. A device, worn like a wristwatch, for measuring movement. Useful in studies of sleep. WinCD will directly process actigraph data files generated by Precision Control Design Inc. actigraphs.

Amplitude. The height of the remodulate signal for a given epoch. Units are the same as the original data.

Append Column. In saving data, WinCD allows the user to add the output epoch-by-epoch data to an existing data file, thus building a database that may be used by other programs for further analysis.

ASCII. American Standard Code for Information Interchange. This code is used for storing what are sometimes called "plain text" files. These files may be created or edited with the Windows "Notepad" or MS-DOS "Edit" programs (as well as all standard word-processors). Note that WinCD will NOT accept any files other than plain text files (with the exception of Actigraph files).

Base Period. The amount of time in the cycle of primary interest. For Circadian Rhythms, this would be 24 hours.

Batch Processing. WinCD allows for automatic processing of a group of files specified in an "Index File", according to settings specified in a "Parameter File".

Complex Demodulation. A procedure for applying a digital band-pass filter to time-series data.

CPD. Cycles Per Day

Cycles per Base Period. The CD parameter that controls the frequency being analyzed. For example if the Base Period is 24 hours, and you are interested in 12-hour cycles, then "Cycles per Base Period" should be set to 2.

Directory. The location of a file on a hard or floppy disk.

Display. The WinCD menu choice that allows the user to specify which of several time series will be graphed on the computer screen.

Detrend. The process of removing a constant or linear trend from the data prior to performing the CD filtering operations. See "Mean" and "Linear Regression".

Drive. The device on which a computer stores data when it is not being used. Typical Drives are hard and floppy disks.

Epoch. The interval of time between observations in a time series.

Epochs in Base Period. Exactly what it sounds like. For example, if observations were made every 30 minutes, and the base period is 24 hours, then there are 48 "epochs per base period.

Filter. The mathematical process used to select a desired frequency from a time series.

Fold-out. The number of data points used in "folding out" a time series.

Folding out. The process used by WinCD to minimize "End effects" in analyzing a time series.

Index File. An ASCII file listing the data files to be batch processed by WinCD. This file must have the file type (extension) "LST".

Linear Regression. The detrending method used by WinCD to eliminate a linear trend from a time series. In doing this WinCD fits a linear function to the entire data set, and subtracts the value of that function at each epoch from the data at that epoch, yielding a "detrended" function.

Linear Trend. The linear function yielded by the linear regression operation.

Mean. The detrending method in which the mean of the entire time series is subtracted from the data for each epoch.

Open. The menu selection used to read data into WinCD.

Output. The process of writing WinCD results into a computer file. All WinCD output files are ASCII files

Parameter File. The file created by the "Batch Processing", "Create Parameter File" option, which contains the information needed by WinCD to perform a Batch job. These files have the file type "CDP".

Peaks. The points at which remodulate functions reach a maximum.

Phase. If the sought-for frequency and the demodulating frequency are conceptualized as a rotating vectors, phase represents the angular difference between the two (see Appendix 1). WinCD provides the phase angle in degrees, not radians.

Print Screen. The menu choice that prints the current screen and any forms on the screen, on the system printer.

Remodulate. The filtered output of a CD operation.

Residual. What remains when the remodulate is subtracted from the detrended data.

Retrend (the remodulate). In both "Save" and "View", checking this box directs WinCD to add back the trend (either mean or linear trend). before putting out the CD results.

Save. The menu selection directing WinCD to write CD results into a computer file. . The default output file type is "CDX".

Trim Output. A check-box option on the "Save" panel for specifying the starting and ending epochs for data to be saved in a WinCD output file.

Use Residuals. Checking this box on the "CD Parameters" panel directs WinCD to use the residuals from a prior CD operation for the next CD operation.

Valleys. The points at which remodulate functions reach a minimum.

View. The WinCD menu choice that allows the user to specify which of several time series will be shown as a numerical table on the computer screen.

Zero-Crossings. The points at which remodulate functions cross zero.

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This document describes WinCD, a program for extracting quantitative information about periodicity in time-series data using the method of Complex Demodulation (CD). The method is particularly well-suited for the analysis of variables that may produce changes in biological rhythms, such as sleep deprivation, adaptation to changes in work schedules, time-zone displacements, and various sorts of pathology (e.g., sleep disorders). WinCD enables exploratory analysis of time-series data by providing graphical displays of raw and processed time series, as well as numerous options for viewing and saving quantitative data. This document presents detailed descriptions of WinCD operations, examples of the use of the program, a discussion of CD theory and background, and a glossary of CD terms. The program and documentation are available for free distribution to interested parties.

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